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1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE January 31, 2006		3. REPORT TYPE AND DATES COVERED Final, June 01, 2002 through October 31, 2005
4. TITLE AND SUBTITLE Ballistic Imaging in the Primary Breakup Region of Diesel Injector Sprays			5. FUNDING NUMBERS DAAD19-02-1-0221	
6. AUTHOR(S) M. A. Linne, T. E. Parker				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Engineering Division Colorado School of Mines Golden, CO 80401			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER 4 2 9 8 7 . 9 - E G	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The Colorado School of Mines (CSM) has developed a technique (called ballistic imaging) for single-shot imaging of the near-field primary breakup region of a diesel spray. Ballistic imaging is a non-intrusive optical measurement technique that produces line-of-sight integrated images. These images represent the underlying spray structure in spite of the droplet cloud which surrounds the interior of the spray. Single shot ballistic imaging relies on an ultra-fast optical "switch;" the optical switch is used to discriminate between ballistic and non-ballistic photons. Note that the ballistic photons contain the "image" information which appears as a range of extinction levels across the imaging beam. This technique has been applied to the breakup region of a high pressure turbulent water jet and to a high pressure diesel spray directed into the ambient environment. Results from the diesel injection indicate harmonic structure at the spray periphery and downstream voids that possibly are formed due to entrainment. Current work is focussed on using this technique with a non-regeneratively amplified laser system (i.e. with a significantly cheaper and more reliable laser system) and on applying the measurement to a diesel spray at diesel relevant conditions using the high temperature and pressure diesel spray facility at CSM.				
14. SUBJECT TERMS Diesel Engine Sprays, Ballistic Imaginng, Infrared Scatterinng			15. NUMBER OF PAGES 18	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

Final Progress Report
Ballistic Imaging in the Primary Breakup Region of Diesel Injector Sprays
Project Number DAAD19-02-1-0221
January 31, 2006

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(1) Foreword - none

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(4) Statement of the problem studied

Diesel sprays and their properties are critical to the emission, ignition, and efficiency performance of all diesel engines. Therefore, sophisticated diesel engine design and analysis models must use an accurate description of the spray and its performance. Unfortunately, the spray breakup process is poorly understood and is influenced by factors such as cavitation, liquid turbulence, and aerodynamic shear. Compounding the problem of uncertain spray breakup physics, is the difficulty of making measurements of the breakup process. These measurements are difficult due to the optical density of the region near the injector tip. A technique known as ballistic imaging has been applied within this work to produce images of the spray breakup region.

Ballistic imaging is a non-intrusive optical measurement technique capable of producing line-of-sight integrated images for highly scattering systems. At the Colorado School of Mines, this technique has been developed with a focus on investigations of the near-field spray-break-up region of diesel sprays. Single shot ballistic imaging relies on a combination of an ultra-fast laser pulse and an ultra-fast optical “switch;” the optical switch is used to discriminate between ballistic and non-ballistic photons and results to-date include diesel injection with injection pressures of 100 MPa (14,000 psi) through an on-axis, single orifice (155 microns) nozzle. These results indicate harmonic structure at the spray periphery and downstream voids that possibly are formed due to entrainment. In addition, we have demonstrated ballistic imaging with a significantly cheaper and more reliable laser system to enable dissemination of the measurement technique throughout the scientific community.

(5) Summary of Most Important Results

Introduction

Within this ARO-supported program, the Colorado School of Mines (CSM) has developed a technique for imaging the near-field, very high liquid volume fraction region in the primary breakup region of a diesel spray which is at the injector outlet. Experimental efforts to date have been for a realistic diesel injection system (a Lucas nozzle mounted in a Sturman Injection system) into the ambient atmosphere. The long-term goal is to perform these measurements under operating temperatures and pressures typical of a diesel engine for a realistic combusting spray. In parallel with this effort, CSM has continued to develop and implement infrared based droplet size and volume fractions for diesel sprays.

Further improvements in diesel engines will be achieved by development of more sophisticated computational design tools, and these must include high quality submodels for injection, breakup, and evaporation¹. Development of such generalized submodels requires a fundamental understanding of each process. Our goal has been (and is) to contribute to the understanding of the primary breakup zone by producing images of this flowfield under realistic conditions and by acquiring quantitative droplet size and volume fraction near the breakup region. CSM is uniquely positioned to produce the measurements at diesel-like conditions using a high pressure and temperature diesel spray combustion facility.

The team working on this project includes Prof. Mark Linne (specializing in ballistic imaging), Prof. Terry Parker (specializing in diesel sprays and scattering/extinction measurement in sprays as well as ballistic imaging), and three graduate students (M. Paciaroni, Ph.D. 2003, T.D. Hall, M.S. 2004, and E. Brooke Walters, Ph.D. candidate). The early part of the program (described in interim progress reports) focused upon optimization of single-shot ballistic imaging for transient diesel spray studies, reported on initial ballistic imaging results to a steady water jet and finally reported on a diesel spray issuing into a one atmosphere ambient surrounding. For the overall contract we can report the following accomplishments:

- Publications:
 - Six Archival Journal publications
 - Eight Conference Presentations
 - Four invited presentations
- Technical Accomplishments:
 - Developed a single shot ballistic imaging system based upon a laser system capable of a 1 mJ, 150 fs pulse
 - Applied this ballistic imaging system to a steady, high pressure water jet
 - Applied this ballistic imaging system to a realistic diesel injection system spraying into the ambient environment.
 - Augmented an existing diesel spray test facility to allow operation at conditions up to 30 atm. The overall facility capability is 30 atm., 1000 K, with a production-like diesel engine spray system.

¹ J.C. Beale and R.D. Reitz, "Modeling Spray Atomization with the Kelvin-Helmholtz/Rayleigh-Taylor Hybrid Model", *Atomization and Sprays*, Vol. 9, 623-650, (1999).

- Work that is still in progress:
 - Optimization of the ballistic imaging system to a new, more powerful and reliable laser system (Continuum Leopard). This conversion required a complete redesign of the optical delivery system for both the image and gate pulse. We are pleased to report that we have acquired ballistic images of the diesel spray with this system and we believe that this is the first of its kind. The ballistic images acquired used a time gate that is dramatically shorter than the parent laser pulse.
 - Acquisition of ballistic images at conditions similar to those in an engine.
- Work in parallel with the ballistic imaging work at CSM has produced:
 - Two-dimensional “movies” of the diesel spray system.²
 - An assessment of the multiple scattering interferences that ultimately limit the application of infrared scattering sizing methods to the spray outlet and breakup region.³

Overview of Results

Figure 1 highlights results from this work and shows a ballistic image from the injector during the steady spray operation. Figure 2 illustrates infrared scattering results (“movie” results were also produced and can be found at http://egweb.mines.edu/TParker-Primary/Diesel%20Spray%20Movies/diesel_spray.htm) and shows the spatially resolved volume fraction for a spray into the ambient environment as well as for a combustive spray. Note that these results start 15 mm from the injector tip. Multiple scattering analyses done by Prof. Parker indicate that accurate measurements can be performed within the combustive spray 10 mm from the spray tip. Regions closer to the spray tip are as yet unexplored with this technique.

As a long term goal, we will apply the ballistic imaging diagnostic to an optically accessible diesel engine simulator used for spray studies at CSM. Finally, we will apply infrared scattering measurements, with multiple scattering corrections, to produce quantitative droplet size and volume fraction measurements as close to the primary spray breakup zone as possible. There is thus a logical evolution from diagnostics development to application, with an emphasis upon the fluid mechanics and development of the spray.

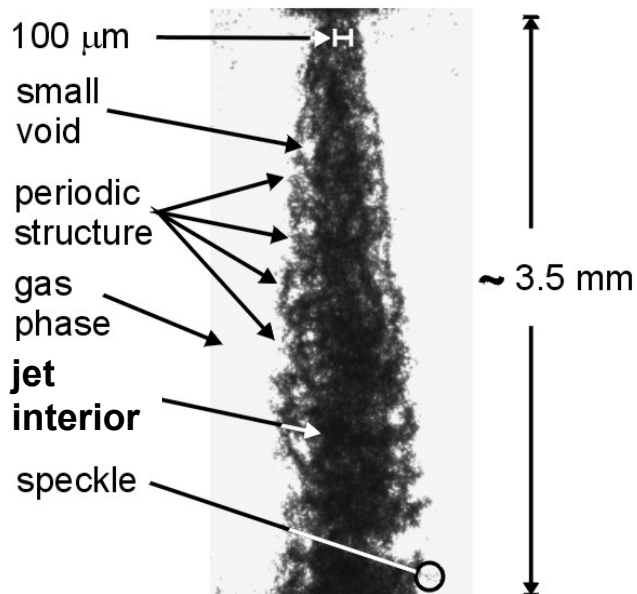


Figure 1. Ballistic image of the fully developed spray.

² Labs, J. and T.E. Parker, *Two-Dimensional Droplet Size and Volume Fraction Distributions from the Near Injector Region of High-Pressure Diesel Spray*, to appear *Atomization and Sprays*, 2006.

³ Labs, J. and T.E. Parker, *Multiple Scattering Effects on Infrared Scattering Measurements used to Characterize Droplet Size and Volume Fraction Distributions in Diesel Sprays*. *Applied Optics*, 2005, **44**(28), p. 6049-6057.

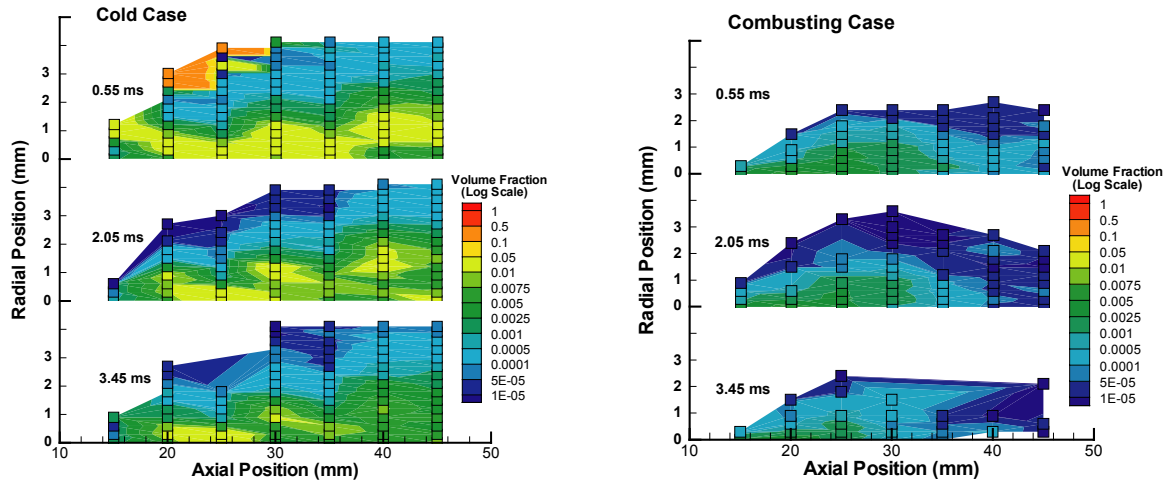


Figure 2. Volume fraction measurements within a diesel spray. Results on the right are for a spray into the ambient 1 atm. environment. Results on the left are for a combusting spray (initial conditions 873 K, 12.5 atm.)

In what follows, we provide a brief description of ballistic imaging (for readers that are unfamiliar with the technique), and then present and discuss important results from the overall effort. Publications generated by this work have appropriately disseminated results to the scientific community.

Background on Time-Gated Ballistic Imaging

The very small amount of light transmitted through turbid material is separated into three components: ballistic, snake and diffuse. Upon exiting the medium, a resultant pulse is typically orders of magnitude longer in time and much weaker than the input pulse. A small group of photons, called “ballistic photons,” propagate directly through the material with no scattering. These photons traverse the shortest path and are the first to exit the material. The second group of photons, called “snake photons,” will be forward scattered minimally and remain within a small forward-directed solid angle. These photons will traverse a slightly longer path and will exit the material just after the ballistic photons. The remaining diffuse photons are scattered quite severely into a large solid angle, take the longest path, and are the last group of photons to exit the material. Figure 3 provides a schematic description of these photons.

Due to their undisturbed path, ballistic photons retain an undistorted image of structures that may be embedded within the turbid material. If used in a shadowgram arrangement, the ballistic photons can provide diffraction-limited imaging of these structures. In contrast, diffuse photons retain no memory of the structure within the material. If allowed to participate in the formation of an image, the various paths these multiply scattered photons take through the material will cause each image point they form to appear as if it came from an entirely different part of the object, and this will degrade resolution. Unfortunately, diffuse photons are the most numerous when light is transmitted through highly scattering media. The problem of obtaining a high-resolution image through highly scattering materials is thus a matter of separating and eliminating the diffuse light from the ballistic and snake light. This can be done using discrimination methods that make use of the properties that are retained by the ballistic and snake light, but are lost in multiple scattering events. The direction and polarization taken by

transmitted light, together with exit time, can help to segregate diffuse photons from the imaging photons. This is done in this work via spatial filtering (to select the light exiting at narrow scattering angles) and polarizers, together with time gating. In time gating, a very fast shutter (an optical Kerr effect (OKE) gate⁴) is used to select just the leading edge containing ballistic and snake photons.

The fluid structures imaged by the ballistic photons fall within the geometric imaging domain. Under normal imaging (i.e. non-ballistic) circumstances, the smallest scale that would be observable would approach the diffraction limit (depending of course upon the optics used in the experiment). As described in more detail elsewhere,⁵ system development work has demonstrated that we can routinely achieve a single-frame spatial resolution around 40-50 μm in scattering environments characteristic of diesel sprays. Among the sprays we have studied, atomizing diesel fuel sprays are the most highly attenuating. This figure of merit (spatial resolution of 40-50 μm) is an approximation to the FWHM of the point spread function (PSF) for the entire optical system. The PSF is a continuous function, meaning that features smaller than the quoted FWHM do not suddenly become invisible. They are certainly detectable, but with reduced image contrast (i.e. with more blur). As features grow successively smaller, image contrast can become eroded to the point where one can comfortably label the feature as "not visible", but it is a continuous progression from what could be called clearly visible to what could be called invisible.

The time-gated ballistic imaging instrument used for initial experiments at CSM is shown in Figure 4. A 1-kHz repetition rate Spectra-Physics Spitfire Ti:Sapphire regenerative amplifier, seeded with a Spectra-Physics Tsunami Ti:Sapphire mode-locked laser, generates 80 fs, 1mJ pulses centered in wavelength at ~ 800 nm. The linearly polarized beam is split into OKE gating and imaging beams; 30% of the optical power is used as the imaging beam while the remaining power is used to create the OKE time gate. A DURIP award has been used to replace the regeneratively amplified Spectra-Physics laser

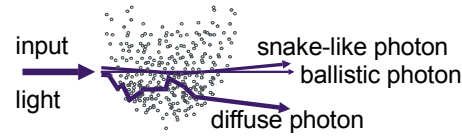


Figure 3a. Geometric schematic of ballistic imaging.

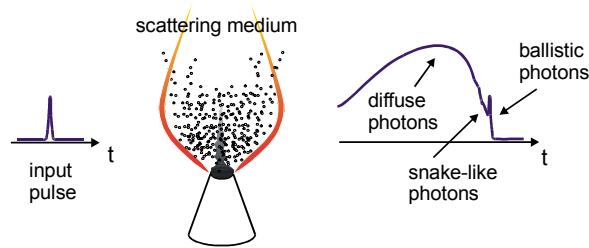


Figure 3b. Time-domain schematic of ballistic imaging with a short pulse.

⁴ Wang, I., P.P. Ho, C. Liu, G. Zhang, and R.R. Alfano, Ballistic 2-D Imaging Through Scattering Walls Using an Ultrafast Optical Kerr Gate. *Science*, 1991. 253: p. 769-771.

⁵ Paciaroni, M. and M. Linne, Single-shot, Two-dimensional Ballistic Imaging through Scattering Media. *Applied Optics*, 2004. 43(26): p. 5100-5109.

system with a single, turn key laser system. This new laser system is quite reliable and easy to operate. However, the change in lasers has required a complete redesign of the optics required for the measurement.

Referring to Fig. 4, the polarization state of the imaging beam is first linearized with a polarizer, because the OKE gate relies upon polarization switching, and then the polarization is rotated 45°. The imaging beam is then time delayed using an adjustable length delay arm that allows one to control the delay between the arrival of the switching and imaging pulses at the OKE gate, for optimum time gating. The imaging beam then passes through an optics train consisting of a telescope (with spatial filter) that controls the imaging beam size at the object, a system to relay the beam through the OKE switch, and a combined spatial filter/telescope for imaging onto a display screen. This optical system was designed and optimized using OSLO®, a commercial ray-trace code. By careful choice of available optics, we have ensured that the optical train itself is diffraction limited; there are no spurious aberrations or distortions introduced by the imaging optics themselves. The OKE gate depends on a pair of polarizers with orthogonal polarization states; the CS₂ Kerr cell is placed between the polarizers. When the switching beam is not present, the image beam passes through the Kerr cell with no change in polarization state and is blocked by the second polarizer. However, the applied electric field from the switching beam produces birefringence in the CS₂ which in turn rotates the polarization state of the image beam. Thus, the application of the switching beam produces a transient polarization rotation in the applied imaging beam. Careful timing of switching and image beam arrival along with a design that produces an effective ½ wave plate at full intensity for the switching beam produces a high speed optical “switch.” This OKE induced birefringence (or switching time) is limited by either the duration of the laser pulse or the molecular response time of the Kerr medium, whichever is longer. For work with the Continuum Leopard, careful relative timing between image and probe beams is required to produce an appropriately short time gate.

Past the OKE gate, the image is relayed to a display screen and the image is captured by a Roper

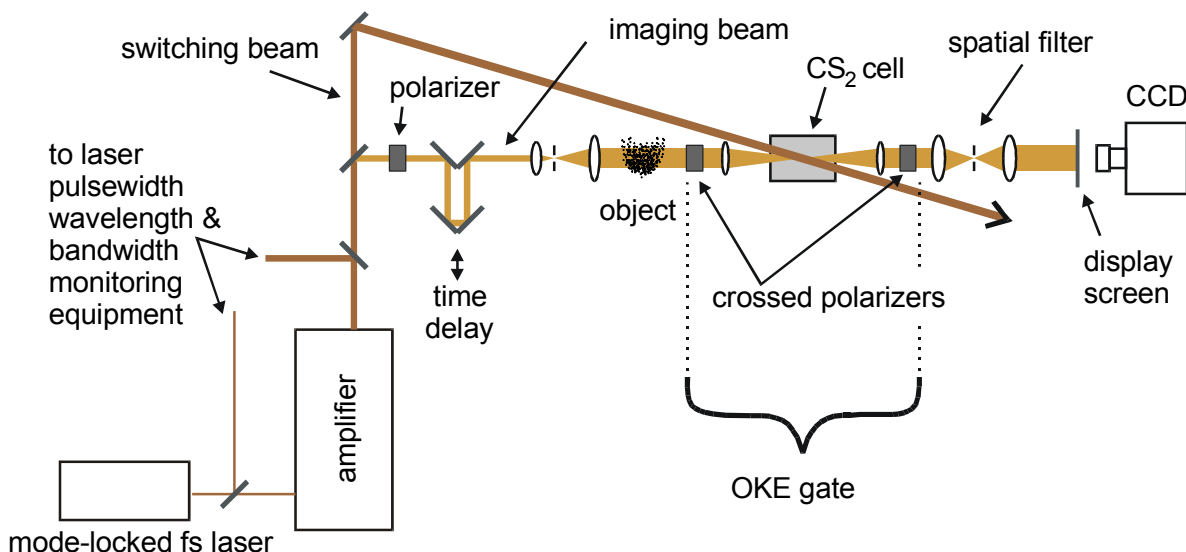


Figure 4. Layout of OKE-switched ballistic imaging system at CSM.

Scientific Cascade 650 CCD camera equipped with on-chip multiplication gain.

Discussion of Ballistic Imaging Results

The spray studied here was produced by a Sturman® diesel fuel injector, which has the capability for multiple injections in a single diesel combustion event. The results presented in this paper were acquired using an on axis, single hole (155 μm) in the injector nozzle. Both commercial diesel fuel and dodecane were evaluated, and the jet issued into still air at ambient conditions (0.8 atm. and approximately 300 K) and injection pressure was 100 MPa.

An example ballistic image of the diesel spray was previously introduced as Fig. 1 and the height of the displayed area depicts roughly 3.5 mm in the object plane. As one examines the images, it must be remembered that they are based upon extinction across the spray field; the ballistic aspect of the measurement simply removes multiply scattered light so that an “image” may be formed. In the image, dark areas represent regions of high extinction levels and light areas represent little or no extinction. The light areas clearly represent regions of gas; interpretation of the regions that are dark is more difficult due to the column integrated nature of the measurement and the fact that either liquid or high volume fraction regions of droplets can both be highly attenuating. The jet itself is quite distinct from the surrounding gas and illustrates a highly structured edge. Clearly the jet is mixing vigorously on the edges and shows features such as voids and periodic structures. One must be careful when interpreting the images because small variations in adjacent regions may simply be due to noise and/or diffraction effects. However, when somewhat organized structures appear at the jet edge and these structures are of significant scale that simple diffraction cannot explain them, one must conclude that the likelihood of the structures in the overall image simply being noise is quite small. The very near nozzle region of these images at this point in time cannot be interpreted due to the very large optical depth at the outlet so that the combination of noise, diffraction, and size make quantitative interpretation difficult.

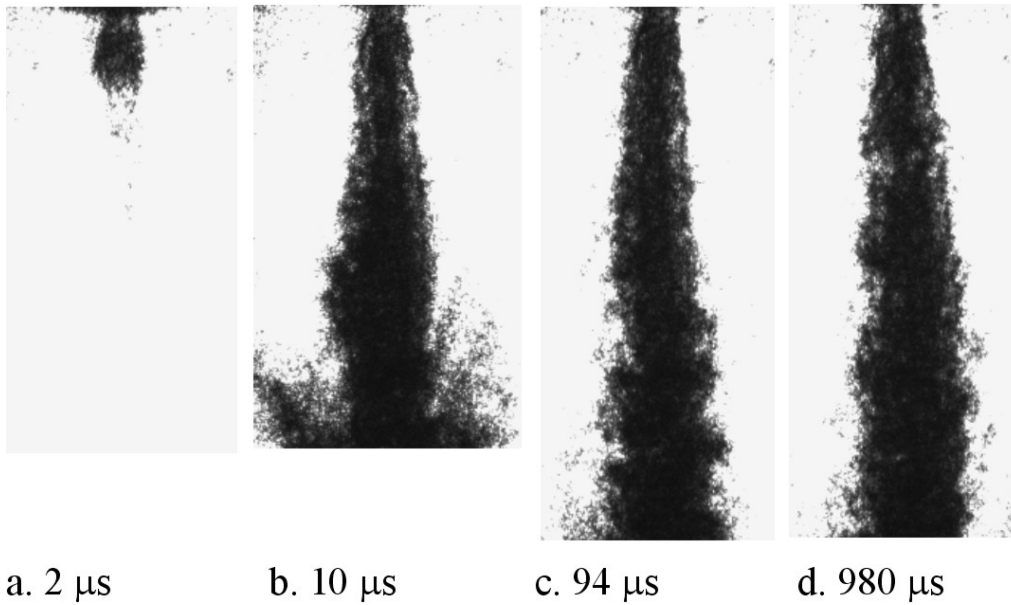


Figure 5. Ballistic images for early times in the spray. Times noted are the image acquisition times after start of injection.

The development of the central jet region at the beginning of an injection event was observed by collecting a series of images of the region surrounding spray tip, for increasing times after the start of injection. Representative images are contained in Figure 5. The very early liquid stream develops a roll-up as it encounters the air, and in some cases this roll-up is penetrated by the oncoming liquid stream as it builds momentum.

These images show that we have proven the ability of OKE-gated ballistic imaging to acquire high-resolution, two-dimensional, single-shot images of the spray breakup region at the nozzle outlet of a transient atomizing diesel spray injected into ambient air. Voids are observed, as are spatially periodic structures. The jet itself appears to consist of a high momentum, high liquid volume fraction (or pure liquid) region that is vigorously mixing with the surrounding fluid.

Recent Results: Ballistic imaging with the Continuum Leopard and Imaging processing

Fig. 6 shows the initial time gated ballistic images taken with the Continuum Leopard laser system. Although we are still improving image quality in the system, these images are very promising. Features at the edge of the spray are apparent with the characteristic fluctuations and voids that are present in the time gated ballistic images typical of the images taken with the spectra physics laser system. Noise in these images is from a combination of the beam and the scattered light from the optical kerr cell. Improvements in beam quality are ongoing, scattered light from the kerr cell will be avoided when we move to a cell switched by the fundamental laser wavelength ($1.06\text{ }\mu\text{m}$ instead of 532 nm), and intensity variations in the image will be partially removed by image processing which accounts for local beam intensity changes. Overall, we are quite pleased with this result as it demonstrates that the Continuum Leopard can be used in ballistic imaging experiments.

Further work with the continuum Leopard has focused on improving imaging performance and on image processing. This work has proceeded without the OKE time gate so the images are ballistic due to spatial rejection of non-ballistic photons; however, the temporal rejection of photons is not present in these images.

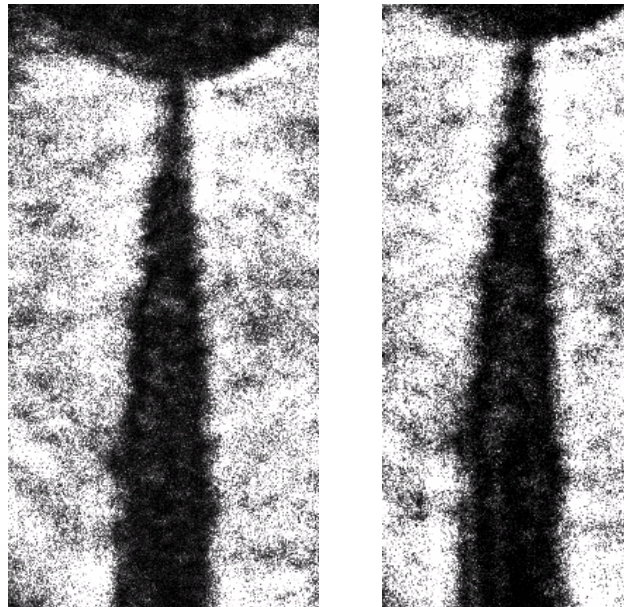


Figure 6. Ballistic images acquired with the Continuum leopard. Note the periodic structures at the spray edge.

Figure 7 is an image of the Sturman Injector spray showing approximately 7.5 mm of the spray; note that this image has been processed to remove the background signal and adjusted for the laser intensity fluctuations across the beam. Both intensity fluctuations and the camera background were quantified by acquiring multiple frames of data (typically 30). Background signal was acquired by operating the camera with the laser off; laser intensity variations were quantified by acquiring multiple images of the beam with the no spray. The color scale on this image is from 0 to 1.0 and is defined as the background subtracted signal at a pixel divided by the background subtracted signal at the same pixel when no spray is present (essentially the image shows the fraction of the original laser intensity that is present at a particular pixel). Image quality is limited for this system by the camera resolution (full frame 653x492 pixels). However, laser intensity fluctuations across the frame are significant and the software correction is working well, as evidenced by the relative uniformity of the field where no spray is present. A special note on the injector tip is in order; laser intensities were acquired with the injector in position. Thus, the signal within the injector tip is not terribly meaningful.

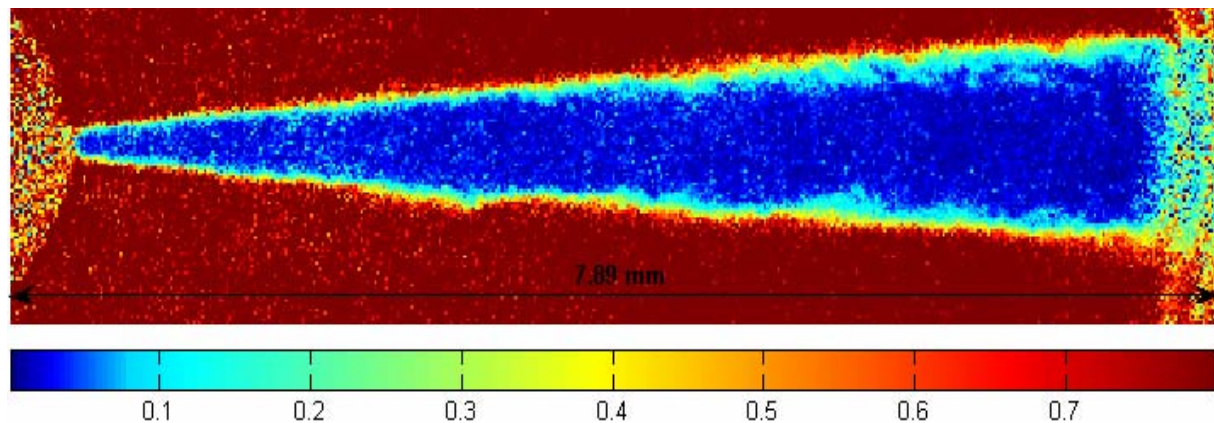


Figure 7. Image of the spray that does not include the time gate, note that resolution is limited by the camera, not by the optical system. The far right side of the image shows significant noise due to intensity falloff of the beam. The scale is fractional intensity with 1.0 being no attenuation of the laser and 0.0 total attenuation of the laser.

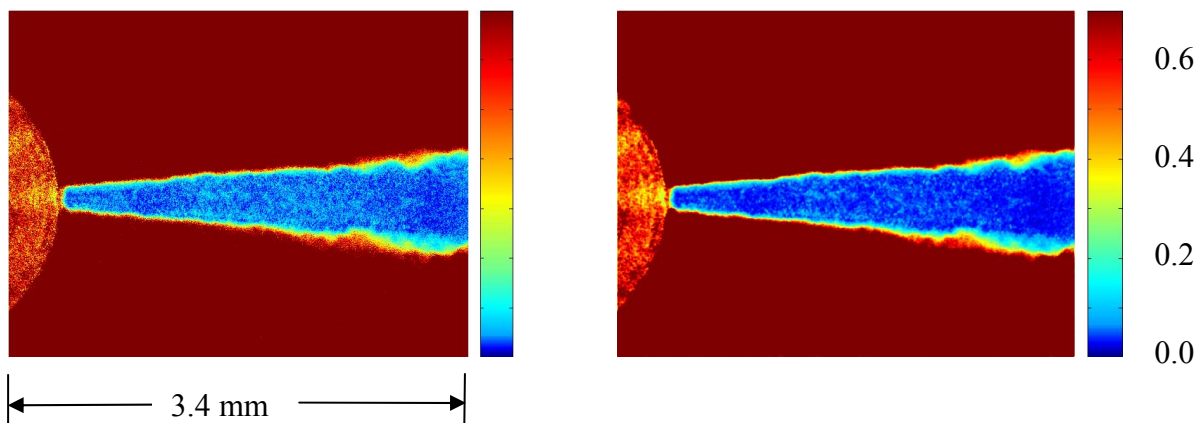


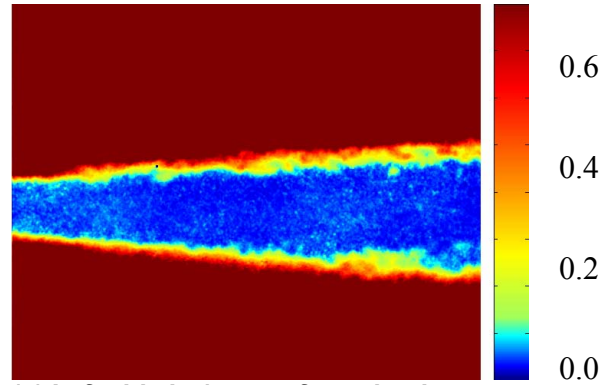
Figure 8. Zoomed in image of the diesel jet. Image on the left is fractional intensity. Image on the right has been filtered with 3x3 box filter. Scale is the fractional intensity of the laser.

Figure 8 shows a smaller field of view for the same spray. In this case the resolution is not limited by the camera array and the image is much sharper. As in other images, as the jet moves away from the orifice, undulations in the interface from the surrounding gas and the jet fluid become more pronounced. Fig. 9 shows a series of images similar to those in Fig. 8 but offset from the injector tip. The interface between jet fluid and surrounding gas becomes much more structured as the fluid moves downstream. The addition of a time gate should improve the image information in this interface region.

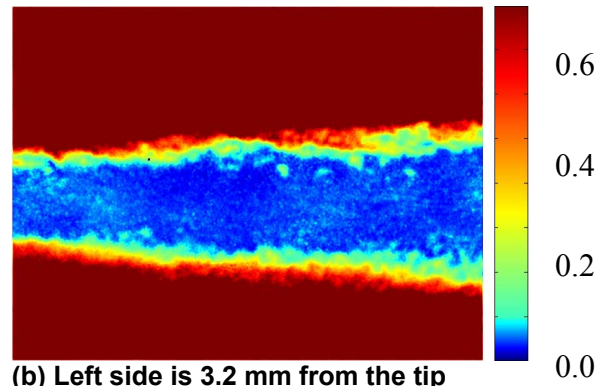
Imaging of breakup dynamics

In a recent collaboration with Air Force Labs, we have demonstrated that a ballistic imaging instrument can be modified to detect the velocity of both the liquid-gas interface of a spray core, and the velocity of primary droplets stripped from the core. Moreover, a simple extension would make it possible to provide images of the force vectors that act to break apart intact liquid features in sprays.

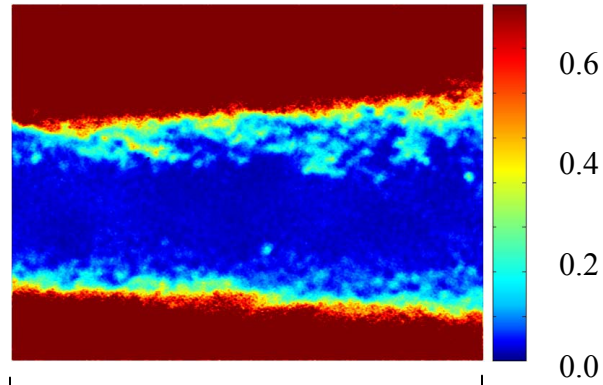
In order to demonstrate velocity imaging, a flow system used for liquid jet in cross-flow research was adapted by shutting off the gas flow and reducing the liquid flow. This generated a steady sequence of falling droplets. This enabled the 1-kHz laser system to illuminate droplet image pairs with sufficient time resolution between successive images. Sprays will require greater than 1-kHz repetition rates, but such laser systems and cameras are commercially available. The image pairs used for this



(a) Left side is 1.5 mm from the tip



(b) Left side is 3.2 mm from the tip



(c) Left side is 6 mm from the injector tip

Figure 9. Images of the diesel jet at various distances from the injector tip. As the jet moves away from the tip, it spreads and the gradient in intensity at the jet- fluid/surrounding-gas boundary becomes much less steep.

proof-of-concept were acquired using an interline transfer CCD capable of storing two images spaced as little as $2\ \mu\text{s}$ apart. To extract velocity, pairs of ballistic images taken at times t_1 and t_2 are analyzed via noise reduction and correlation algorithms. An example image is shown in Figure 10.

If one could obtain at least three or four images taken at sufficiently short intervals, it would be possible to apply a similar method to mitigate uncertainties and to obtain acceleration vectors.

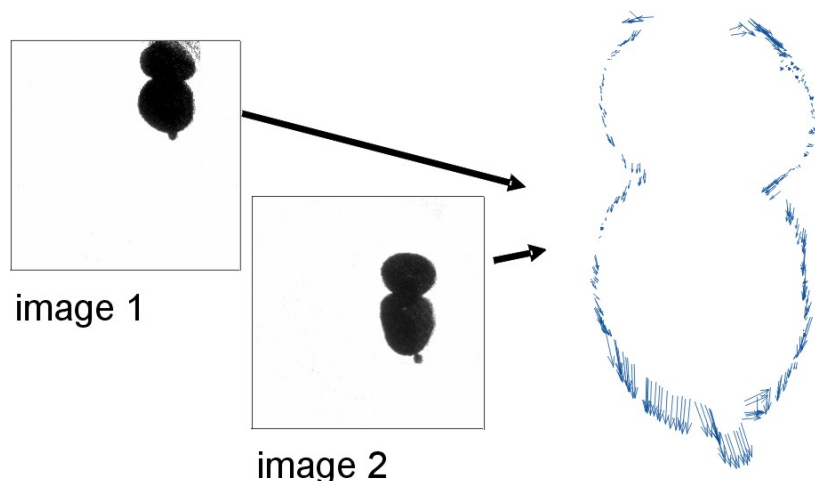


Figure 10. Droplet images with velocity vectors. Droplet diameter is on the order of $500\ \mu\text{m}$.

Laser systems with the appropriate speed are commercially available, and four images can be acquired with two double image cameras suitably aligned with each other. Other components of the instrument (e.g. the OKE gate) are not rate limiting.

From acceleration data, given some knowledge about the composition of the liquid and gas under observation, one could determine forces acting on the features tracked by our method. This capability can, for the first time, resolve unambiguously the dynamics that break apart the liquid core in the near field.

Conclusions

This ARO supported program has been focused on production of diagnostics capable of monitoring processes in diesel sprays. Ballistic imaging has been applied to a realistic diesel spray providing the first of their kind pictures of the break up region in a diesel jet. In addition, ballistic imaging has been demonstrated with a simple to use laser system (the Continuum Leopard); this facilitates the dissemination of the technique to other laboratories. Finally, the ballistic imaging instrument has been used to produce images of the breakup dynamics between droplets.

(6) Publication List

(a) Papers published in peer reviewed journals

1. Mark Linne, Megan Paciaroni, Tyler Hall, and Terry Parker, "Ballistic Imaging of the Near Field in a Diesel Spray", *Experiments in Fluids*, to appear 2006.
2. David Sedarsky, Megan Paciaroni, Mark Linne, James Gord, and Terry Meyer, "Velocity imaging at the fluid/gas interface of the liquid core in an atomizing spray", *Optics Letters*, to appear 2006.
3. Megan Paciaroni, Tyler Hall, Jean-Pierre Delplanque, Terry Parker and Mark Linne, "Single-Shot Two-Dimensional Ballistic Imaging of the Liquid Core in an Atomizing Spray", *Atomization and Sprays*, **16**, no. 1, 2006.
4. Mark Linne, Megan Paciaroni, James Gord and Terry Meyer, "Ballistic Imaging of the Liquid Core for a Steady Jet in Crossflow", *Applied Optics*, Vol. 44, No. 31, pp. 6627-6634, 2005.
5. Megan Paciaroni and Mark Linne, "Single-shot two-dimensional ballistic imaging through scattering media", *Applied Optics*, **43**, No. 26, pp. 5100-5109, 2004.
6. Labs, J.E., J. Filley, E. Jepsen, and T.E. Parker, *A Constant Volume Diesel Spray Combustion Facility and the Corresponding Experimental Diagnostics*. Review of Scientific Instruments, 2005. **76**(3): 11 pp.

(b) Papers published in conference proceedings

1. "Ballistic Imaging of the Liquid Core for a Steady Liquid Jet in a Gaseous Crossflow", Mark Linne, Megan Paciaroni, James Gord and Terrence Meyer, presented at ILASS Europe, Orelans, FR, September 5 - 7, (2005).
2. "The Structure of the Very Near Field for a Diesel Spray: Results from a Ballistic Imaging Study", M. A. Linne, M. E. Paciaroni, D. Sedarsky, T. Hall and T. Parker, Fifth Symposium: Towards Clean Diesel Engines, Lund, Sweden, June 2-3, (2005).
3. "Ballistic Imaging of the Liquid Core for a Jet in Cross-Flow", Mark Linne, Megan Paciaroni, James Gord and Terry Meyer, presented at ILASS Americas, Irvine CA, May 22 – 25, (2005).
4. "The Structure of the Very Near Field for a Diesel Spray: Results from a Ballistic Imaging Study", E. Brooke Walters, T. Hall, M. Paciaroni, M. Linne, and Terry Parker, presented at ILASS Americas, Irvine CA, May 22 – 25, (2005).
5. "Ballistic Imaging for the Liquid Core of an Atomizing Spray", Megan Paciaroni, Mark Linne, Tyler Hall, Jean-Pierre Delplanque, and Terry Parker, presented at the 19th Annual ILASS-Europe, Nottingham, England, September, (2004).
6. "Ballistic Imaging in the Liquid Core of a Spray", M. A. Linne, M. Paciaroni, T. Hall, T. Parker, presented at Laser Applications to Chemical and Environmental Analysis, Annapolis, MD, February, (2004).
7. "Ballistic imaging in the liquid core of a fuel spray", M. Linne, presented at the 25th Annual Task Leaders meeting, IEA Implementing Agreement on Energy Conservation and Emissions Reduction in Combustion, Faringdon, UK, Sept. 7-10, (2003).
8. "Ballistic imaging for the liquid core of a liquid fuel spray", M. Paciaroni, T. Hall, T. Parker, and M. A. Linne, presented at the joint Scandinavian-Nordic and Italian section meeting of the Combustion Institute, September, (2003).

(c) Presentations not including a publication

1. “Ballistic Imaging for the Near Field in an Atomizing Spray”, to be presented to the Frontiers in Spectroscopy program at Ohio State University, March 9 & 10, (2006).
2. “Ballistic Imaging for the Near Field (Liquid Core?) in an Atomizing Spray”, invited seminar presented to the Department of Energy and Power (EKT), Technical University of Darmstadt, (2005).
3. “New Developments in Ballistic Imaging for Dense-Spray Diagnostics”, J. R. Gord, T. R. Meyer, M. Paciaroni, D. Sedarsky, and M. A. Linne, selected as a “Hot Topic” special presentation to the Gordon Conference on the Physics and Chemistry of Laser Diagnostics, Mt. Holyoke, MA, (2005).
4. “Ballistic Imaging in Turbid Media: Application to Sprays”, presented to the Gordon Conference on the Physics and Chemistry of Laser Diagnostics, Oxford, UK, (2003).

(7) Scientific Personnel and degrees earned

Professor Mark Linne

Professor Terry Parker

Dr. Megan Paciaroni (Ph.D. degree earned during the project)

Mr. Tyler Hall (M.S. degree earned during the project)

Ms. E. Brooke Walters (currently in the Ph.D. program)

(8) Report of Inventions

None

(9) Bibliography

References included as footnotes within the text

(10) Appendices

None